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# Precision Higgs Physics at a Future Linear Collider

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Assuming that a Higgs sector is responsible for electroweak symmetry breaking, we attempt to address two important questions: How much better precision are various measurements of Higgs boson properties at a future linear collider than at the LHC? What can a future linear collider do for Higgs physics that the LHC cannot?

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# 1 Introduction

The origin of electroweak symmetry breaking (EWSB) and fermion mass generation remains one of the most pertinent in the field of high energy physics today. Although there exist several explanations for EWSB, some dynamical and others spontaneous, preeminent among those is the existence of a Higgs sector, either one or two complex scalar doublets which acquire a vacuum expectation value (vev), or vevs, providing longitudinal degrees of freedom for the weak gauge bosons and additional physical observable Higgs boson states. For a single Higgs doublet, as in the Standard Model (SM), one neutral CP even Higgs ( $H$ ) would be observed. In a two-Higgs doublet model (2HDM), such as the MSSM, five physical Higgses would exist: light and heavy CP even neutral scalars ( $h, H$ ), a CP odd scalar ( $A$ ), and a charged Higgs and its conjugate  $H^\pm$ . Additionally, a set of Yukawa couplings of the Higgs to SM fermions ( $Y_f$ ), of unknown origin, generates the fermion masses.

No physical Higgs boson has yet been observed, although electroweak precision data has long suggested that the Higgs is light, of order 100 GeV. As such, it can possibly be accessed by present experiments, i.e. CERN’s LEP II or the Fermilab Tevatron II. If neither of those experiments turns up evidence for a Higgs, the community will turn to the LHC, which will have the capability to detect a SM or at least one MSSM Higgs of any mass up to the unitarity limit.

Let us suppose that the LHC finds a Higgs candidate resonance, which could be either the solitary physical Higgs of a single Higgs doublet model, or a 2HDM neutral state. This could be confirmation of previous observation at LEP or Tevatron, or an LHC discovery. Either way, a narrow resonance  $\phi$  is found in one or more anticipated channels with rate commensurate with expectations. The task is then to determine the quantum numbers of  $\phi$ , first to confirm that it is a Higgs of some flavor, second to determine what model the Higgs belongs to. These quantum numbers are, with the expected value for a Higgs in brackets:

- charge [neutral]
- color [none]
- mass [ $\mathcal{O}(100)$  GeV]
- spin [0]
- couplings (gauge, Yukawa) [model dependent]
- total width
- self-coupling ( $\lambda$ ) [model dependent]
- CP [even, odd, mixture?]

The nature of the final state of the observed channel(s) gives us at least the first two quantum numbers, charge and color, immediately. For example, detecting a Jacobian peak in the dilepton-missing transverse momentum spectrum in  $\ell^+\ell^- jj\cancel{p}_T$  events, as expected in weak boson fusion and decay to a pair of  $W$  bosons, would indicate that the state is neutral and colorless. Likewise for finding a resonance in the two photon invariant mass spectrum, i.e. due to Higgs production,  $gg \rightarrow \phi \rightarrow \gamma\gamma$ . The latter process would further imply by Yang's Theorem that the state cannot be spin 1, also consistent with a Higgs boson. A fairly precise measurement of the state's mass would also be obtained.

These determinations are necessary, but not sufficient conditions for confirming the Higgs nature of an observed resonance. To go further we must measure the state's coupling to weak bosons, which must be a gauge coupling, perhaps modified by a mass mixing parameter  $\alpha$  and ratio of vevs in a 2HDM  $\tan\beta$ ; and its couplings to fermions, which must be Yukawa, i.e. proportional to the fermion mass. Were these couplings found to meet the requirements of a Higgs sector, it is likely that most members of the community would agree that a Higgs had been discovered. However, the issue of measuring a self-coupling clouds this. One could argue that this is merely an aspect of determining the exact model that is realized in nature. To this end we would also want to know the CP state of the resonance.

For a SM or MSSM Higgs, the LHC can, in fact, make quite good determinations of the mass and gauge coupling, a very good measurement of the total width (even for a Higgs width smaller than the width resolution of the detectors), and a good measurement of at least one Yukawa coupling,  $Y_\tau$  [1]. CP-dependent distributions in Higgs production are known [2], however observing them appears not to be possible in practice, due to detector effects [3]. A future International Linear Collider (ILC) can certainly do better than the LHC for the case of a light Higgs, approximately  $110 \leq M_H \leq 200$  GeV. How much better an ILC could measure these couplings, what additional couplings it would have access to, and its ability to go significantly beyond LHC physics by measuring a self-coupling  $\lambda$  or the CP nature of the Higgs sector are what I review here.

## 2 The Easy Quantum Numbers

Of greatest interest in Higgs physics is “Where is the Higgs?” That is, what is its mass? Precision fits to electroweak data suggest [4] it is very near the lower bound from experiment,  $M_H > 113$  GeV [5]. If a Higgs is found in the range  $M_H < 135$  GeV or so, then the MSSM is still a viable theory. Finding a much heavier Higgs would suggest a different form of new physics. At the LHC,  $M_H$  would be determined principally by observing the process  $gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$ , which is accessible at all masses. For example, at ATLAS for  $M_H < 400$  GeV, this would yield a 0.1%

or better mass measurement, depending ultimately on uncertainty in the calorimeter calibration [3].

For a light Higgs, an ILC would improve this roughly by a factor of two to three, around  $0.03 - 0.05\%$  uncertainty for a light Higgs, using a combination of data from the recoil mass spectrum in  $e^+e^- \rightarrow HZ \rightarrow \ell^+\ell^- + X$  and direct reconstruction of Higgs decay into dijets. A simulated recoil mass spectrum for  $M_H = 120$  GeV is shown in Fig. 1. Fig. 2 shows a comparison between CMS expectations and some different ILC energies and luminosities. However, this level of precision may be overkill. It would correspond to, for example, 4-loop radiative corrections in the MSSM! These are currently far from achievable. Additionally, the leading uncertainty in  $\Delta M_H$  in this case is due to the large uncertainty in the top quark mass,  $m_t$ , which will not improve enough in the LHC or conceivable ILC experiments to warrant calculation of MSSM 4-loop corrections to  $M_H$ , possibly even the 3-loop contributions.

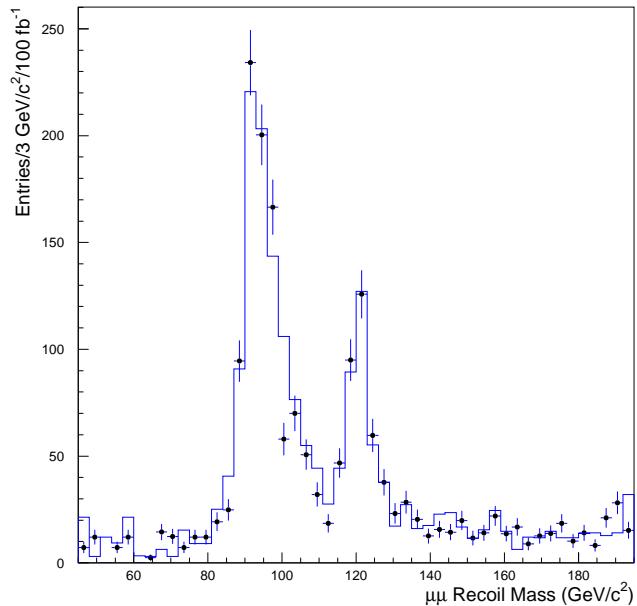


Figure 1:  $\mu\mu$  recoil mass for  $e^+e^- \rightarrow ZH \rightarrow \mu\mu + X$ , taken from Ref. [6].

Determining consistency of a resonance with spin-0 has been studied thoroughly for the LHC. There exist two methods: angular distributions in  $H \rightarrow \gamma\gamma$ , and also in the reconstructed  $Z$  bosons in  $H \rightarrow ZZ$  [3]. The LHC has no difficulty with this consistency check for  $M_H < 400$  GeV, so I do not discuss it further here.

Measurement of the resonance's couplings to the weak bosons, photon, gluons, and fermions is of much greater interest. Confirming that  $g_{HWW}, g_{HZZ}$  are gauge couplings and related by SU(2) is one of the key determinations to identifying the resonance as a Higgs boson. These couplings may be modified by mixing or other parameters of a 2HDM, which are well defined and appear only as overall factors.

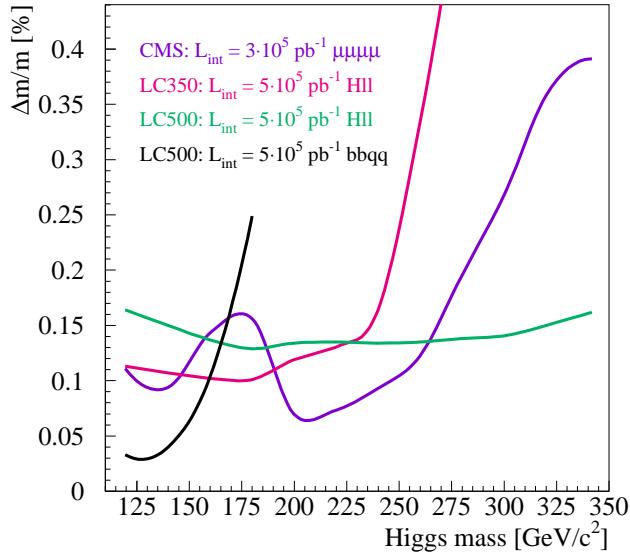


Figure 2: The expected Higgs mass resolution at CMS and at three linear collider options, taken from Ref. [7].

For example, the  $hWW$ ,  $HWW$  vertices are modified at tree level in the MSSM by  $\sin(\beta - \alpha)$ ,  $\cos(\beta - \alpha)$ , respectively. In this same vein, we would require that  $g_{H\gamma\gamma}$ ,  $g_{Hgg}$  are demonstrated to be loop-induced.

At the LHC,  $g_{HWW}$  may be determined to better than 5% for a light Higgs,  $M_H < 200$  GeV, for scenarios where the Higgs is relatively SM-like [1]; non-SM-like Higgs coupling extraction scenarios are just now beginning to be examined [8]. This is achieved by combining information from various decay channels in weak boson fusion Higgs production. This same method also allows the total width to be extracted indirectly, to about the 10 – 15% level. The best Yukawa coupling measurement can be made for taus, which is quite good at about 5 – 15% over the mass region  $115 < M_H < 150$  GeV, and work is progressing on  $H \rightarrow b\bar{b}$  but this measurement is not likely to be better than about 30% in the end [9]. Decays to  $c\bar{c}$  are completely inaccessible at the LHC, but the width to gluons could be determined to about 20% from the rate for  $gg \rightarrow H \rightarrow W^+W^-$  and the highly accurately known  $\text{BR}(WW)$ . These results would already be quite good and allow for considerable model determination, but an ILC could do far better.

The procedure for extracting couplings<sup>1</sup> is equally involved at the ILC. First, the recoil mass spectrum in  $ZH$  production would be used to determine  $\sigma_{ZH}$  to about

<sup>1</sup>We may alternatively discuss the measurement of partial widths, which are directly proportional to the coupling squared. If the total width cannot be determined, it is more appropriate to discuss measurement of branching ratios.

2% (TESLA) for a light Higgs, say  $110 < M_H < 150$  GeV. This measurement is the basis for extracting absolute branching ratios. Once the  $WW$  branching ratio is known (< 5% for a light Higgs, possibly as good as 2%),  $g_{HWW}$  could be obtained to better than 2%. From there, Yukawa couplings could be extracted directly. The expected uncertainty in the branching ratio for decay to  $b\bar{b}$  is anticipated to be the lowest, about 2% for  $M_H = 120$  with reasonable luminosity; 8% for  $c\bar{c}$  and 6% for  $\tau^+\tau^-$ . Additionally,  $\text{BR}(gg)$  could be determined to about 8% for the same mass. Fig. 3 shows the probable branching ratio measurement precision at TESLA.

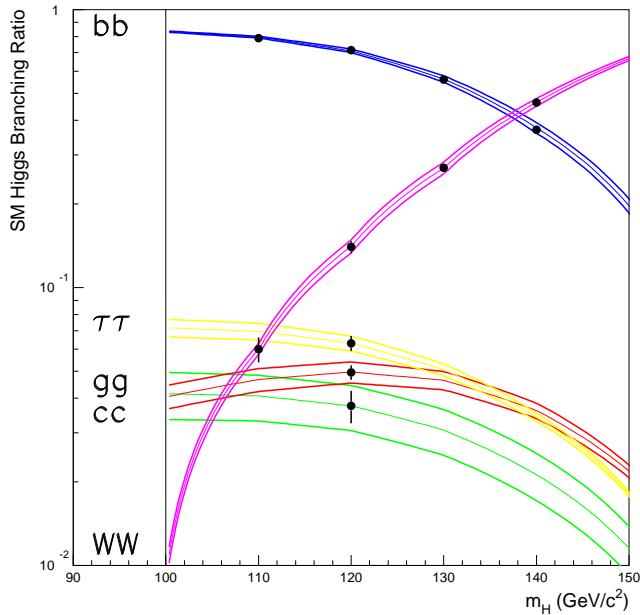


Figure 3: Estimated accuracy for SM Higgs branching fractions for  $500 \text{ fb}^{-1}$  of data at TESLA, taken from Ref. [6].

$t\bar{t}H$  production is possible for a high-energy ILC, being optimum at about  $\sqrt{s} = 800$  GeV for  $M_H = 120$  GeV. There is considerable discrepancy in the literature, however, as to the achievable precision in  $\delta g_{Htt}/g_{Htt}$ , ranging from 6% [10] on the optimistic end to as pessimistic as about 50% [11]. Clearly, more study is needed to resolve this disagreement. Finally, the total width could be had to better than 5% for  $M_H = 120$  GeV, or about 3% for  $M_H = 140$  GeV, using the  $H\nu\nu$  cross section as key input, which contains the already determined gauge coupling.

As far as distinguishing the SM from the MSSM, prospects appear good at the ILC but this subject begs for more study. Ratios of branching ratios are important, especially  $\text{BR}(b\bar{b})/\text{BR}(W^+W^-)$ , which could yield an indirect measurement of  $M_A$ . (It is possible that observing the CP odd state  $A$  itself could prove difficult.) Other important ratios are  $\text{BR}(c\bar{c})/\text{BR}(b\bar{b})$  and  $\text{BR}(gg)/\text{BR}(b\bar{b})$ . It is known that an MSSM Higgs sector can be established as non-SM-like at the 95% CL for  $M_A < 550$  or so at

TESLA, depending somewhat on  $\tan\beta$ . This is shown in Fig. 4 for  $500 \text{ fb}^{-1}$  of data.

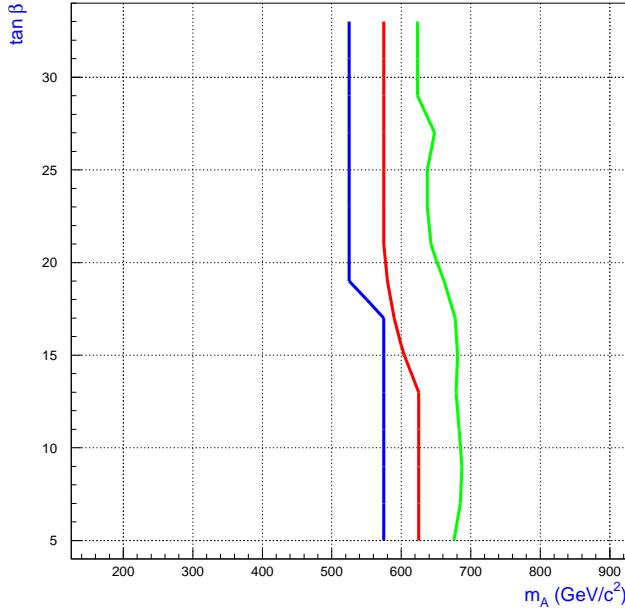


Figure 4: SM v. MSSM discriminating power as a function of  $M_A$  and  $\tan\beta$  for  $500 \text{ fb}^{-1}$  of data at TESLA, taken from Ref. [6]. Parameter space to the right of the curves would appear SM-like. The blue curve is 95% CL, red is 90% CL, and green is 68% CL.

For a Higgs heavier than about 150 GeV, measurement of Yukawa couplings (other than to the top quark) are essentially inaccessible at any machine, except in certain restricted regions of a 2HDM. However, it is still highly desirable to know the gauge couplings and total width in this regions. Preliminary results indicate [12] that for the mass region  $150 < M_H < 300$  GeV an ILC could achieve 10% uncertainty for  $\text{BR}(WW)$  and 10 – 25% uncertainty for  $\text{BR}(ZZ)$ , the latter depending strongly on  $M_H$ . For  $M_H > 300$  GeV,  $\text{BR}(VV)$  could be determined to a few percent, and  $\text{BR}(t\bar{t})$  becomes accessible, probably at the 6% level. It is currently not known how to measure this at all at the LHC. For  $M_H > 230$  GeV or so, the Higgs width is expected to exceed detector resolution; the LHC and an ILC would have comparable ability here, at the few percent level for a heavy Higgs. A heavy Higgs is widely regarded as less interesting, and as such this scenario has not received as much attention in studies for an ILC.

It is easy to find already in the SM that radiative corrections are important. For example,  $\delta \text{BR}(b\bar{b}) > 30\%$  for  $M_H = 120$  GeV, simply due to the gluonic corrections. In extensions to the SM, such as the MSSM, large radiative corrections to the couplings (partial widths) lurk behind every corner. To take a couple examples, light squark corrections to  $h \rightarrow gg$  can be as large as factors of 2-3 in the partial width, but disappear as the squarks get heavy, greater than a few hundred GeV. Also, gluino

or chargino corrections to the  $b$ - $H$  vertexies and  $H_1, H_2$  mixing can lead to order 1 corrections to the partial widths to  $b$  quarks or  $\tau$  leptons [13]. Considerable effort has been invested in calculating such corrections over the past decade, but the state of the art advances and interesting phenomenology continues to be revealed.

### 3 The Tough Quantum Numbers

While the “easy-to-determine” quantum numbers of a newly discovered resonance may be sufficient to establish it as part of a Higgs sector, in some sense the more difficult measurements are the interesting ones. These are the CP nature of the resonance, more specifically if there is any CP mixing in the neutral states in the case of a two Higgs doublet sector; and the self-coupling(s)  $\lambda_i$ . In the SM  $\lambda$  is related to the Higgs mass via  $M_H^2 = 2v^2\lambda$ , and as it is a free parameter,  $M_H$  is undetermined. In the MSSM, the various  $\lambda_i$  are gauge couplings, thus  $M_H$  is constrained. To be convinced that an observed Higgs sector (and perhaps other MSSM candidate states) belong to the MSSM, we would need to verify that these are, indeed, gauge couplings. Thus, multiple Higgs production would have to be observed.

Several studies have addressed the issue of multiple Higgs production at an ILC, highlighting scenarios where the cross section is large enough to obtain a substantial rate [14]. Only two groups have performed a signal v. background study at the phenomenological level (in the  $ZHH$  channel for the SM), and only one of those two groups, Castanier et al., included detector simulation. However, their results are quite promising. For a light SM Higgs, i.e.  $120 < M_H < 140$  GeV, their study suggests that the  $ZHH$  cross section could potentially be measured at the 12 – 18% level for large integrated luminosity,  $2000 \text{ fb}^{-1}$ . They further show that this would translate to about a 20% measurement of  $\lambda_{hhh}$ . It is clear that studies such as these at a future linear collider will depend critically on  $b$ -tagging performance. The studies go on to point out that in some MSSM parameter space regions, heavy Higgs decay to lighter Higgs states has significantly larger rates than the SM case, making the prospects for observation quite good. In contrast, it remains to be shown that the LHC has any capability to measure a Higgs sector self-coupling.

Research into methods to extract the CP nature of observed neutral Higgses is even less developed. Studies so far indicate that a  $\text{CP} = +1$  state can be qualitatively distinguished from a  $\text{CP} = -1$  state via angular distributions in  $ZH$  production [15], but if the state has mixed CP, the -1 component is very easily washed out. Additional work is sorely needed in this area, as the LHC again has no capability here, primarily due to the strong backgrounds and detector effects that hide the relevant distributions.

## 4 Conclusions

Prospects for observing a Higgs sector as the responsible mechanism for EWSB are quite good: precision fits to electroweak data suggest that the Higgs is light and thus accessible, perhaps by the Tevatron, and the LHC has the capability to observe a Higgs boson of any mass up to the unitarity limit. While the Tevatron could not make any serious measurements of couplings or other important properties of an observed resonance to completely convince one that it is part of a Higgs sector, the LHC can go a long way toward this goal. The LHC would determine the mass to a greater precision than can be matched theoretically, and would be able to determine the gauge coupling and total width of a Higgs boson, either directly or indirectly, to better than the 10% level. However, the LHC will have considerable difficulty to observe most fermionic decays, and will not have the capability to observe any self-couplings or identify CP mixing among the states of multiple physical Higgses.

An ILC extends our knowledge of a Higgs sector considerably. Its measurements of both gauge and Yukawa couplings would be superior over most of the mass range of a possible Higgs, and it would have access to additional fermionic decays as well as self-couplings and probably CP mixing, improving model discrimination. However, the state of the art on the last goal is still somewhat underdeveloped. Also lacking is a detailed overview of the capability of an ILC to distinguish different models based on coupling and mass measurements, although at least one study to address this is nearing completion [16]. So far, studies have presented levels of measurement precision based only on cross sections in the SM. If a Higgs sector turns out to be not very SM-like, then some of these levels of precision could be quite poor, while others are better than expected, and the restriction in model parameter space may or may not be satisfactorily small.

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